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Green Extraction of Bioactive Compounds from Fruit Processing By-Products: Technologies, Challenges and Food Applications

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Abstract

The increasing generation of fruit-processing waste has created both environmental challenges and opportunities for the recovery of valuable bioactive compounds. Peels, seeds, pomace, pulp residues, and other fruit by-products contain substantial amounts of polyphenols, flavonoids, carotenoids, dietary fibre, essential oils, vitamins, and other functional constituents. Conventional extraction methods often require large quantities of organic solvents and considerable energy, encouraging the development of greener and more sustainable alternatives. Green extraction technologies, including ultrasound-assisted extraction, microwave-assisted extraction, pulsed electric fields, supercritical fluid extraction, pressurized liquid extraction, and enzyme-assisted extraction, can improve the recovery of bioactive compounds while reducing solvent consumption and environmental impact. Recovered compounds have potential applications in functional foods, beverages, nutraceuticals, food packaging, and natural food preservation. This review briefly discusses major fruit-processing by-products, emerging green extraction technologies, associated challenges, and opportunities for their incorporation into food products.

Keywords: *Fruit by-products, green extraction, bioactive compounds, polyphenols, flavonoids, sustainable food processing, functional foods.*

1. Introduction

The global fruit-processing industry generates large quantities of residues during juice production, canning, drying, pulping, and other processing operations. These residues commonly include peels, seeds, stones, pomace, pulp, and fibrous materials. Traditionally, a substantial proportion of these materials has been discarded or used as low-value animal feed. However, many fruit by-products contain higher concentrations of certain bioactive compounds than the edible portions of the fruits [1]. Fruit peels may be rich in phenolic compounds, flavonoids, carotenoids, essential oils, and dietary fibre, whereas seeds can provide oils, proteins, phenolics, and other valuable constituents. Citrus peels, apple pomace, grape pomace, pomegranate peel, mango kernels, and banana peels are therefore increasingly investigated as potential sources of functional ingredients [2].

The recovery of these compounds is consistent with the principles of a circular bioeconomy, in which waste streams are converted into valuable products. However, conventional extraction methods frequently depend on solvents such as methanol, ethanol, acetone, or hexane, together with prolonged heating and high energy consumption. Green extraction approaches aim to overcome these limitations by reducing solvent use, energy requirements, processing time, and environmental impact while maintaining or improving extraction efficiency [3].

2. Major Fruit By-Products and Valuable Bioactive Compounds

Different fruit-processing residues contain different classes of bioactive compounds. Their composition depends on fruit variety, maturity, cultivation conditions, processing conditions, and storage.

Table 1. Important fruit-processing by-products and their major bioactive constituents

Fruit by-product	Important bioactive compounds	Potential applications
Citrus peel	Flavonoids, essential oils, pectin, phenolics	Beverages, preservatives, nutraceuticals
Grape pomace	Anthocyanins, resveratrol, phenolic acids, fibre	Functional foods, supplements
Pomegranate peel	Ellagitannins, flavonoids, phenolic acids	Antioxidant ingredients, food preservation
Apple pomace	Polyphenols, pectin, dietary fibre	Bakery products, beverages, fibre supplements
Mango peel	Carotenoids, mangiferin, phenolics	Functional foods and nutraceuticals
Banana peel	Phenolics, carotenoids, dietary fibre	Bakery products, functional ingredients
Fruit seeds	Phenolics, proteins, essential fatty acids	Oils, protein ingredients, nutraceuticals

These compounds have attracted attention because of their antioxidant, antimicrobial, anti-inflammatory, and metabolic activities. Nevertheless, extraction and purification procedures must be carefully optimized to preserve their biological activity.

3. Green Extraction Technologies

3.1 Ultrasound-Assisted Extraction

Ultrasound-assisted extraction (UAE) uses acoustic waves to generate cavitation within the extraction medium. The resulting physical effects can disrupt plant tissues and facilitate the release of intracellular compounds. UAE generally requires less solvent and shorter extraction times than conventional techniques and has been successfully applied to fruit peels and pomace for the recovery of phenolics, flavonoids, and pigments [4].

3.2 Microwave-Assisted Extraction

Microwave-assisted extraction (MAE) uses microwave energy to rapidly heat the extraction system. Rapid heating can increase cell disruption and improve the transfer of bioactive compounds into the solvent. MAE can significantly reduce extraction time; however, excessive temperatures may degrade heat-sensitive compounds. Optimization of microwave power, extraction time, solvent composition, and solid-to-liquid ratio is therefore important.

3.3 Enzyme-Assisted Extraction

Enzyme-assisted extraction employs enzymes such as cellulases, pectinases, and hemicellulases to break down structural components of plant cell walls. This approach can improve the release of phenolic compounds, pigments, oils, and other intracellular constituents [5]. It is particularly attractive for fruit by-products because many residues contain substantial quantities of pectin and structural polysaccharides.

3.4 Supercritical Fluid Extraction

Supercritical fluid extraction commonly uses supercritical carbon dioxide as an extraction medium. The technique offers the advantages of low solvent residues, selective extraction, and relatively mild operating conditions. It is particularly useful for recovering non-polar compounds such as essential oils, carotenoids, and lipid-soluble constituents. Its major limitation is the relatively high equipment and operating cost compared with simpler extraction technologies [6].

3.5 Pressurized Liquid and Other Emerging Technologies

Pressurized liquid extraction employs elevated temperature and pressure to enhance solvent penetration and solubilization of target compounds. Other emerging approaches, including pulsed electric fields, high-voltage electrical discharge, deep eutectic solvents, and natural deep eutectic solvents, are also being explored for sustainable recovery of plant bioactives.

Natural deep eutectic solvents are particularly interesting because they can be prepared from relatively benign components and may provide improved extraction selectivity. Nevertheless, their safety, biodegradability, residual levels, and suitability for food applications require further investigation.

Table 2. Comparison of selected green extraction technologies

Technology	Main advantage	Common target compounds	Major limitation
UAE	Short extraction time and low solvent requirement	Phenolics, flavonoids	Process optimization required
MAE	Rapid heating and efficient extraction	Phenolics, pigments	Heat-sensitive compounds may degrade
Enzyme-assisted extraction	Efficient cell-wall disruption	Phenolics, proteins, oils	Enzyme cost
Supercritical CO_2	Low solvent residue and selectivity	Oils, carotenoids, essential oils	High equipment cost
Pressurized liquid extraction	Efficient solvent penetration	Phenolics and antioxidants	Requires specialized equipment
Natural deep eutectic solvents	Tunable extraction properties	Phenolics and flavonoids	Food-safety and recovery issues

4. Food Applications

The bioactive compounds recovered from fruit-processing by-products can be incorporated into a wide range of food products. Phenolic-rich extracts can potentially be used as natural antioxidants or preservatives, while fruit fibres and pectin can improve the nutritional and technological properties of bakery products, beverages, sauces, and snacks. Grape and pomegranate extracts, for example, have considerable potential as sources of natural antioxidants. Citrus-derived compounds can provide both functional and sensory properties, while fruit pomace powders can increase dietary fibre content in cereal-based products [7]. Recovered pigments such as anthocyanins and carotenoids may also serve as natural colouring agents. However, their application is influenced by pH, temperature, light, oxygen, and interactions with other food components. Encapsulation can help improve the stability of sensitive compounds and facilitate their incorporation into beverages and functional foods.

Another promising application is active food packaging. Phenolic extracts and essential oils derived from fruit residues can be incorporated into packaging materials to provide antioxidant or antimicrobial activity, potentially extending the shelf life of perishable foods [8].

6. Conclusion

Fruit-processing by-products represent an underutilized reservoir of valuable bioactive compounds and functional ingredients. Green extraction technologies provide promising approaches for recovering phenolics, flavonoids, carotenoids, essential oils, dietary fibre, and other compounds while reducing solvent use and environmental burdens. Ultrasound-, microwave-, enzyme-, supercritical-fluid-, and pressure-assisted extraction methods can improve extraction efficiency when appropriately optimized.

The recovered ingredients have potential applications in functional foods, beverages, nutraceuticals, natural preservatives, and active packaging. Future development should focus on scalable, economically viable, safe, and environmentally sustainable extraction systems capable of converting fruit-processing residues into high-value food ingredients within a circular bioeconomy.

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